A High-Resolution X-Ray Study of SN 1006
– Chandra’s Large Project View and Prospects for ASTRO-H –

Satoru Katsuda$^1$, P. Frank Winkler$^2$, Brian J. Williams$^3$, Stephen P. Reynolds$^4$, Robert Petre$^3$, Knox S. Long$^3$, Una Hwang$^3$, and Sean Ressler$^4$

$^1$ RIKEN (The Institute of Physical and Chemical Research) Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
$^2$ Department of Physics, Middlebury College, Middlebury, VT 05753, USA
$^3$ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
$^4$ Physics Department, North Carolina State University, Raleigh, NC 27695, USA

E-mail(SK): satoru.katsuda@riken.jp

Abstract

We present results from a deep (670 ks) X-ray survey of the entire SN 1006 remnant using the Chandra X-ray Observatory. Proper-motion measurements of the entire periphery reveal that the southeastern periphery has the highest velocity of $\sim 7400$ km/s, almost 2.5 times that in the northwest. Emission-line equivalent width images show that Si-rich ejecta are especially prominent in the southeastern quadrant, indicating large-scale asymmetries arising from the explosion itself, while O and Mg are more uniformly distributed, suggesting substantial contributions from the interstellar medium. We have expanded the search for precursor X-ray emission ahead of a synchrotron-dominated shock front, as expected from diffusive shock acceleration theory, to numerous regions along both the northeastern and southwestern rims of the shell. Our data require that a precursor be thinner than about 3$''$, and fainter than about 5% of the post-shock peak. These limits suggest that the magnetic field is amplified to values of order 100 $\mu$G in a narrow precursor region, promoting diffusive particle acceleration. We also present prospects for ASTRO-H observations of SN 1006, especially focusing on the soft X-ray spectrometer.

Key words: ISM: individual (SN 1006) — ISM: kinematics and dynamics — supernovae: individual (SN 1006) — supernova remnants — X-rays: individual (SN1006) — X-rays: ISM

1. Introduction

SN 1006 is the closest ($d \sim 2.2$ kpc: Winkler et al. 2003) and least obscured ($N_{\text{H}} \sim 7 \times 10^{20}$ cm$^{-2}$: Dubner et al. 2002; Uchida et al. 2013) among historical Type-Ia supernova remnants (SNRs). Its angular diameter of $\sim 30'$ makes it well suited for spatially-resolved spectroscopy. The X-ray emission is dominated by nonthermal emission along its northeastern (NE) and southwestern (SW) limbs, while the X-rays from the other fainter regions are dominated by thermal emission mostly arising from reverse-shocked ejecta (e.g., Koyama et al. 1995). Therefore, SN 1006 has been a very important target for both nonthermal physics and studies of SN Ia explosions.

SN 1006 has been a target for continuing investigation from the current generation of X-ray telescopes: Chandra, XMM-Newton (Vink et al. 2003; Rothenflug et al. 2004; Acero et al. 2007; Broersen et al. 2013; Miceli et al. 2012; 2013; 2014), and Suzaku (Yamaguchi et al. 2008; Bamba et al. 2008; Uchida et al. 2013). The first Chandra observations were a pair of deep pointings in 2000 and 2001 with the Advanced CCD Imaging Spectrometer (ACIS) S-array along the contrasting NE and northwestern (NW) rims in 2001, reported by Long et al. (2003), Bamba et al. (2003), and Allen et al. (2008), followed in 2003 by a mosaic of ACIS-I fields that covered the entire remnant (Cassam-Chenaï et al. 2008), and in 2008 by a second-epoch ACIS-S observation of the NE rim (Katsuda et al. 2009; 2010). The Chandra observations we report here, a Cycle 13 Large Project Observation, were designed as a follow-up to those by Cassam-Chenaï et al. (2008) with nearly five times greater exposure, in order to give a more detailed look at small-scale features and to give a second epoch for measuring the expansion.

2. Observations

The S-array was used for the NE and NW rims (ObsIDs 9107 in 2009 and ObsID 13737 in 2012, respectively) in order to match earlier ACIS-S pointings for proper-motion measurements along those parts of the shell. All the other pointings were made with the ACIS-I array and
were carried out in 2012 April-July. These observations comprise pointings at 10 overlapping fields for a total of 670 ks. The mosaic image in the soft (0.5-1.2 keV, shown in red), medium (1.2-2.0 keV, shown in green), and hard (2.0-7.0 keV, shown in blue) bands is shown in Figure 1.

3. Proper-Motion Measurements

To study the expansion around the entire shell, we have used as the first-epoch image that obtained from a set of eleven overlapping ACIS-I exposures from 2003 (Cassam-Chenaï et al. 2008), each with an exposure time of about 20 ks. Before measuring the proper motions, we have registered images from the two epochs, by aligning a number of X-ray point sources detected in both of the two epochs.

In Figure 2 we show the measured expansion as a function of azimuthal angle (measured in the conventional sense, rotating eastward from north). We extracted radial profiles in 10° azimuthal sectors from the merged images for both 2003 and 2012. We then carried out a minimum-χ² analysis limited to the outermost edge of clear X-ray emission to determine the shifts. The procedure is similar to that we used in earlier analyses of the NE and NW rims (Katsuda et al. 2009; 2013). The proper motions measured here are mostly consistent with our previous results obtained for the NE and NW rims, assuring robustness of our measurements.

The most notable fact about the proper-motion measurements is that the expansion velocity in the southeast (SE: 140° – 170°) is higher than anywhere else around the shell: \( \sim 7400 \pm 800 \text{ km s}^{-1} \), almost 2.5 times faster than that of the far brighter thermal X-ray filament in the NW. In the SE, the shock front is not really defined at all in X-rays (Figure 1); instead the outermost emission is marked by tufts that we interpret as SN ejecta based both on their kinematics and their spectra. Furthermore, some of these tufts are located beyond the outermost of the multiple indistinct shells seen in Hα.

4. Line-Emission Equivalent Width Maps

In order to investigate the spatial distribution of emission from different elements stemming from SN ejecta or from the interstellar medium (ISM), we have produced line equivalent width (EQW) images, according to the similar procedure to that introduced by Hwang et al. (2000) for Cas A. We have focused on K-line emission for significant elements: O, Ne, Mg, and Si.

The EQW images are shown in Figure 3. In all four images, the NE and SW rims have very low values, since strong synchrotron emission there dominates any thermal emission. Within the interior, however, there are distinct differences. Silicon, expected to stem primarily from the ejecta in a Type Ia SN, is strongly concentrated in the NE quadrant—suggesting a clear asymmetry in either the distribution of Si ejecta or in the (presumably reverse) shock pattern that has heated it. This confirms the recent Suzaku result from Uchida et al. (2013). Oxygen and magnesium show less extreme concentrations in
the SE, and also concentrations well inside the shell rim to the NW. These too probably arise largely from SN ejecta, with significant contributions from the shocked ISM. Neon is strongly concentrated in a narrow filament immediately behind the NW shock front where the overall thermal emission is strongest (Figure 1). It seems certain that this feature arises from the shocked ISM.

5. X-Ray Shock Precursors?
A prediction of diffusive shock acceleration theory is that accelerated electrons will spend some of their time ahead of the shock, producing synchrotron emission in a faint “halo” of emission. This halo has yet to be conclusively identified in any young SNRs, but SN 1006 probably presents the best opportunity to detect such a halo thanks to its proximity, low absorption, and well-defined synchrotron rims. The expected scale length for any preshock emission would be close to the diffusive scale length $\kappa/v_{\text{shock}}$ for a parallel shock, where $\kappa$ is the diffusion coefficient defined as $\lambda c/3$ with $\lambda$ being the mean free path and $c$ being the speed of light. For Bohm diffusion, $\lambda$ is just $r_g = eE/B$, and $\kappa = \lambda c/3 = r_g c/3$. Therefore, the diffusive scale is $20 r_g$ or about $3 \times 10^{16} \text{ cm}$ for $5000 \text{ km} \text{s}^{-1}$ shock seen in SN 1006.

To search for such a halo emission, we have selected six regions shown in Figure 4: four along the NE rim and two along the SW. All of the regions are located in places where the local shock front is nearly linear, oriented perpendicular to the front. After subtracting the local background, we have measured the surface brightness averaged over three narrow angular ranges ahead of the shock: $0''$–$5''$, $5''$–$10''$, and $10''$–$15''$. The results are given in Table 1. We see small excesses over the local background for the X-ray flux $0''$–$5''$ ahead of the shock. However, there are a number of factors other than a true halo that could give faint emission ahead of the peak: curvature across the region, projection effects along the line of sight, faint point sources that were not excised, and/or intrinsic PSF response; there is as yet no plausible way to make the shock jump appear sharper than it really is. A fair conclusion of our results is that halo emission in the 1–4 keV range is typically narrower than $3''$. This is consistent with previous measurements for the NE rim based on observations from 2001 (Long et al. 2003). A halo on this scale would require $B > 45 (\mu/0.48 \mu G yr^{-1})^{-2/3}(\theta/3''')^{-2/3}(d/2.2 \text{ kpc})^{-4/3} \mu G$.

6. Prospects for ASTRO-H
The next X-ray astronomy satellite, ASTRO-H, scheduled to be launched in early 2016, will allow us to pursue high-resolution X-ray spectroscopy for diffuse sources, since it will have a nondispersive X-ray spectrometer (the soft X-ray spectrometer, SXS: Mitsuda et al. 2010) with excellent spectral resolution of FWHM~$5\text{ eV}$ . The SXS will provide insight into some of important questions on general astrophysics, using SN 1006 as an example.

One obvious motivation to observe SN 1006 would be to measure expansion velocities along the line of sight by...
separation of red- and blue-shifted components of each line. An example SXS simulation showing O Heα lines is presented in Fig. 5, in which both red- and blue-shifted components for Heα resonance and forbidden lines are clearly resolved. Combining the expansion measurement with the X-ray proper motion determined by Chandra, we can obtain an independent (and probably the most reliable) measurement of the distance to SN 1006. This will not be subject to uncertainties in the shock models based on optical Balmer lines (e.g., van Adelsberg et al. 2008), so that the newly-derived distance will provide a good opportunity to test the shock models.

We can also measure ion temperatures by the line widths. Combining the electron temperature measured from the shape of the continuum emission and line intensity ratios, we can determine electron-ion temperature nonequilibrium at various locations. Furthermore, for the nonthermal-dominated NE and SW rims, it is expected to detect effects of nonthermal particles on thermal emission: either the lines are narrower than expected from the shock speed (e.g., Hughes et al. 2000; Helder et al. 2009), or the lines are broader than expected due to atomic interactions with accelerated ions (Tatischeff et al. 1998). It will be also possible to detect faint lines from low-abundance odd-Z elements such as Al and Mn. In addition to these intriguing topics, we expect surprising discoveries from real data.

7. Conclusions

We have presented a concise overview of Chandra’s Large Project observations of SN 1006 in 2012. Expansion of the entire rim is revealed to be ~5000 km s\(^{-1}\) at the NE and SW rims, ~3000 km s\(^{-1}\), and ~7500 km s\(^{-1}\) at the SE rim. Based on line equivalent width images, Si-rich ejecta are found to be especially prominent in the southeastern quadrant, indicating explosion asymmetries. Our data place significant constraints on a possible X-ray halo in front of any of the synchrotron-dominated regions along the NE or SW rims. There is slight evidence for a faint precursor on scales of less than 3\(''\), indicating the magnetic-field strength upstream to be > 45 \(\mu\)G. In addition to these, there are many future studies to be performed using the rich Chandra data set. Also, high-resolution spectroscopy, which will be available with the advent of ASTRO-H, is desired to obtain new insight into shock physics as well as SNR dynamics.

References

Mitsuda K. et al. 2010, SPIE, 7732, 773221I
Takahashi T. et al. 2012, SPIE, 8443, 84431Z
Yamaguchi H. et al. 2008, PASJ, 60, S141